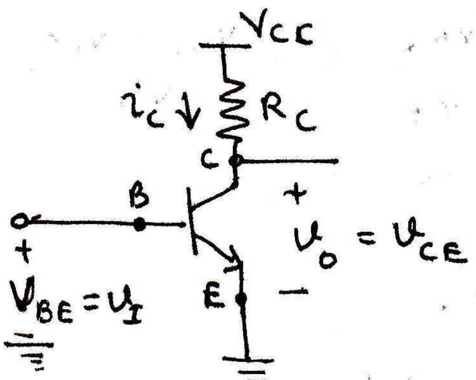
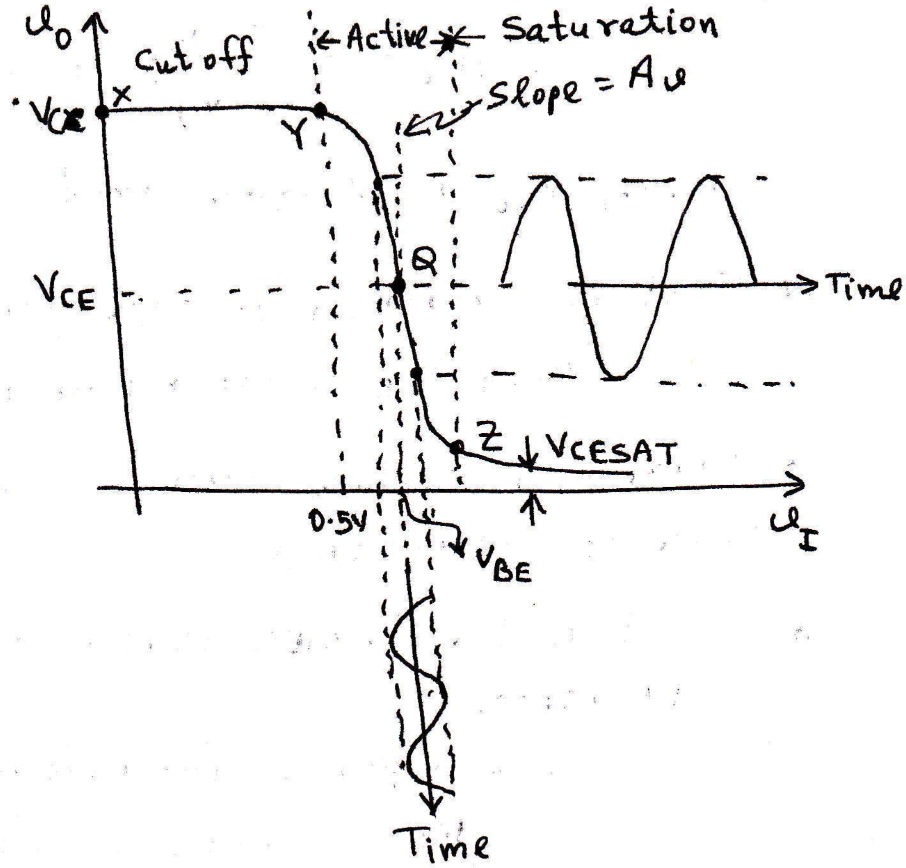
BIPOLAR AMPLIFIERS

COMMON EMITTER LARGE SIGNAL CHARACTERISTIC





Here,
$$v_o = V_{CC} - I_C R_C.$$

In active mode,
$$v_o = V_{CC} - R_C I_S e^{V_{BE}/V_T}.$$

In saturation region, $v_{CE} = V_{CESAT}$ (which is around 0.2 to 0.3V)

$$I_{C,SAT} = \frac{V_{CC} - V_{CESAT}}{R_C}.$$

*Amplifier gain is defined in Active region.

$$A_v = \left.\frac{\partial V_o}{\partial v_I}\right|_{v_I = v_{BE}}$$

$$\Rightarrow A_v = \left.\frac{\partial\left[V_{CC} - R_C I_S e^{V_{BE}/V_T}\right]}{\partial V_I}\right|_{v_I = V_{BE}}$$

$$\Rightarrow A_v = -\frac{1}{V_T} I_S e^{V_{BE}/V_T} \cdot R_C$$

$$\Rightarrow A'_v = -\frac{I_C R_C}{V_T} = -\frac{V_{RC}}{V_T} = -\frac{V_{CC} - V_{CE}}{V_T}$$

where, V_{RC} is voltage drop across R_C.

* What is maximum voltage gain?
  → When V_{CE} is minimum i.e. $V_{CE,SAT}$.

* Maximum voltage gain is obtained when BJT is at edge of saturation.

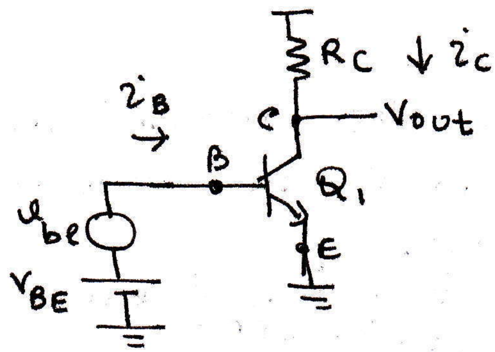
* What is the repercussion of biasing at the edge of saturation?
  → Can you swing below $V_{CE,SAT}$?
  No. ⇒ signal is clipped.

* Theoritical maximum gain is,

$$A_{v,max} \cong -\frac{V_{CC}}{V_T}.$$

* How is this different from MOSFET?
  → Does the designer have control over the gain in BJT?
  → How about in MOSFET?

Example:-



$I_S = 10^{-15}$ A

$R_C = 6.8\,K\Omega$

$V_{CC} = 10\,V.$

(i) What is V_{BE} if $V_{CE} = 3.2\,V$?

$$I_C = \frac{V_{CC} - V_{CE}}{R_C} = \frac{10 - 3.2}{6.8 \times 10^3} = 1\,mA.$$

$$\Rightarrow V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) = 690.8\,mV.$$

(ii) What is the voltage gain? If $v_{be} = 5 \times 10^{-3} \sin(2\pi f t)$ what is v_{out}?

$$A_v = -\frac{V_{CC} - V_{CE}}{V_T} = -\frac{10 - 3.2}{0.025} = -272\,V/V.$$

Thus,

$$v_{out} = -5 \times 10^{-3} \times 272 \sin(2\pi f t)$$

$$\Rightarrow v_{out} = -1.36 \sin(2\pi f t).$$

(iii) What value of v_{BE} drives Q_1 into saturation? Assume $V_{CE,SAT} = 0.3\,V$.

At saturation, $I_C = \dfrac{10 - 0.3}{6.8 \times 1000} = 1.617\,mA.$

New, $V_{BE} = V_T \ln\left(\dfrac{1.617 \times 10^{-3}}{1 \times 10^{-15}}\right) = 702.8\,mV.$

$$\Rightarrow \Delta V_{BE} = 702.8 - 690.8 = 12\,mV.$$

(iv) What value of V_{BE} drives Q_1 into ~~cut off~~ 1% of cut off (i.e. $V_o = 0.99\,V_{CC}$).

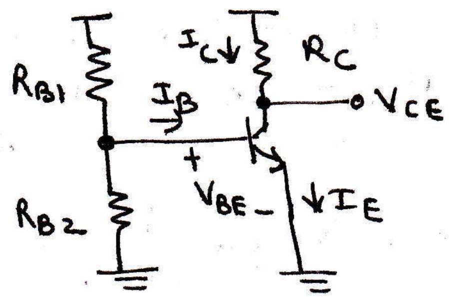
$$I_C = \frac{V_{CC} - 0.99\,V_{CC}}{6800} = 14.7\,\mu A.$$

$$\Rightarrow V_{BE} = V_T \ln\left(\frac{14.7 \times 10^{-6}}{1 \times 10^{-15}}\right) = 585.3\,mV.$$

$$\Rightarrow \Delta V_{BE} = -105.5\,mV.$$

Biasing Schemes for BJT :-

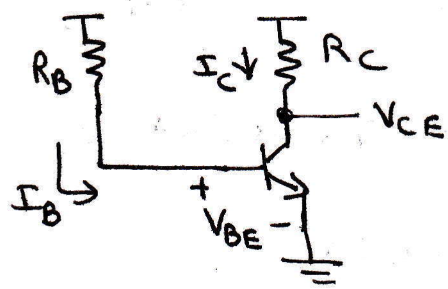
① Fixed V_{BE} :-



* Sharp $I_C - V_{BE}$ characteristic results in drastic changes in bias point.
* Similar to constant V_{GS} biasing for MOSFET.

Not very useful

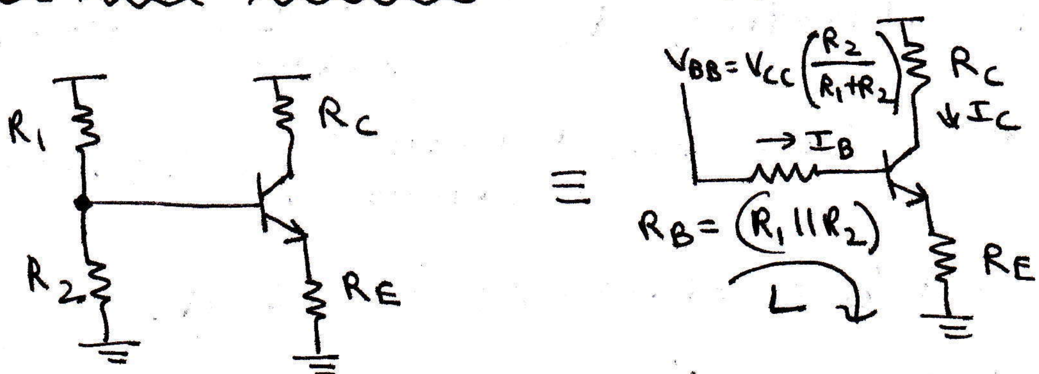
② Fixed I_B :-



* Changes in β can cause drastic changes in bias point.

Not very useful.

③ Biasing Using Resistor Divider & Emitter Degeneration



Writing KVL in loop "L" we get,

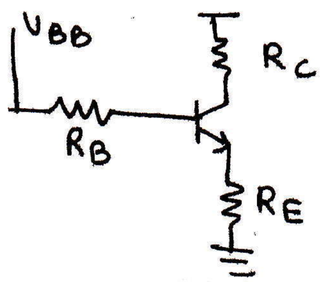
$$V_{BB} = I_B R_B + I_E R_E + V_{BE}$$

$$\Rightarrow \quad I_E = \frac{V_{BB} - V_{BE}}{R_E + R_B/(\beta+1)}.$$

* If $V_{BB} >> V_{BE}$ & $R_E >> \frac{R_B}{\beta+1}$,

I_E is insensitive to transistor parameter variation (Robust biasing)

*



How large can V_{BB} be?

→ Larger the value of V_{BB} ⇒ sum of voltage drop across R_C and V_{CB}.

→ We want large voltage drop across R_C for higher gain and large signal swing befor transistor cut-off.

→ We also want V_{CB} (or V_{CE}) to be large for larger swing befor transistor enters saturation.

⇒ Conflicting requirement. (Your calibre comes into picture).

* No tool is yet good enough for designing automatically.

* ANALOG DESIGN IS ART.

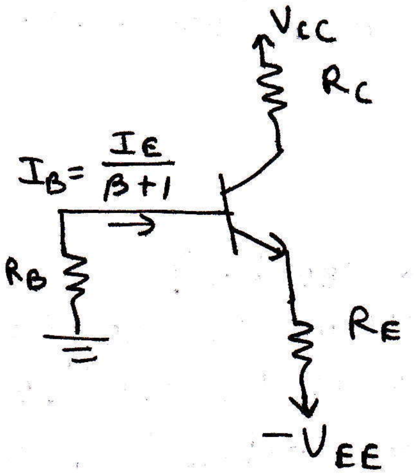
TYPICAL RULE OF THUMB:-

$$V_{BB} \approx \frac{1}{3} V_{CC}$$

$$V_{CB} \approx \frac{1}{3} V_{CC}$$

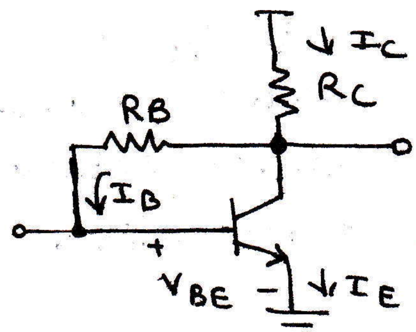
and $I_C R_C \approx \frac{1}{3} V_{CC}$.

Two-Power Supply Version of Classical Bias Arrangement



$$I_E = \frac{V_{EE} - V_{BE}}{R_E + R_B/(\beta+1)}$$

Biasing Using A Collector-Base Feedback Resistor



$$V_{CE} = V_{BE} + I_B R_B.$$

Applying KVL from V_{cc} to ground we get,

$$V_{cc} = I_E R_c + I_B R_B + V_{BE}$$

Why $I_E R_c$, not $I_c R_c$?

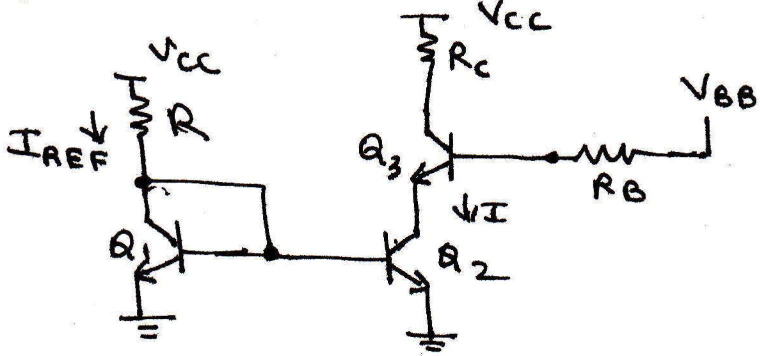
$$\Rightarrow V_{cc} = I_E\left[R_c + \frac{R_B}{\beta+1}\right] + V_{BE}$$

$$\Rightarrow \cancel{V_{cc}}\ I_E = \frac{V_{cc} - V_{BE}}{R_c + R_B/(\beta+1)}$$

* Value of R_B determines V_{CB} and hence allowable signal swing,

$$V_{CB} = I_B R_B = I_E \frac{R_B}{\beta+1}$$

BIASING USING CONSTANT CURRENT SOURCE :-



* Q_1 is diode connected.

$$I_{REF} = \frac{V_{CC} - V_{BE}}{R}.$$

* Since, Q_1 & Q_2 have same V_{BE}, their collector currents will be equal resulting in,

$$I = I_{REF} = \frac{V_{CC} - V_{BE}}{R}.$$

* Arrangement of Q_1, Q_2, & R is called current mirror.

SMALL SIGNAL OPERATION AND MODELS :-

Convention :-

$$v_{BE} = \underset{\text{DC}}{V_{BE}} + \underset{\text{AC}}{v_{be}}$$

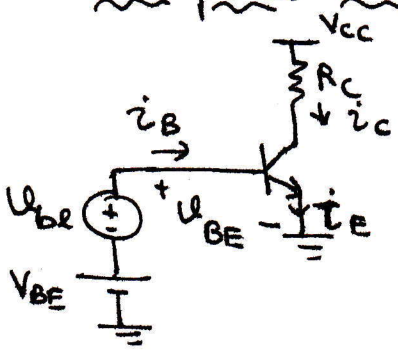
$$v_{CE} = V_{CE} + v_{ce}$$

$$i_C = I_C + i_c$$

$$i_B = I_B + i_b$$

$$i_E = I_E + i_e$$

Conceptual circuit to arrive at small signal model :-



At DC (i.e. no ac signal applied).

$$I_C = I_S e^{V_{BE}/V_T}$$

$$I_E = I_C/\alpha$$

$$I_B = I_C/\beta$$

$$V_C = V_{CE} = V_{CC} - I_C R_C$$

With ac signal :-

$$v_{BE} = V_{BE} + v_{be}$$

$$\Rightarrow i_C = I_C + i_c$$

$$\Rightarrow i_C = I_S e^{(V_{BE}+v_{be})/V_T}$$

$$\Rightarrow i_C = I_S e^{V_{BE}/V_T} e^{v_{be}/V_T}$$

$$\Rightarrow i_C = I_C e^{v_{be}/V_T}$$

$$\Rightarrow i_C = I_C \left(1 + \frac{v_{be}}{V_T}\right) \quad \ldots$$ [By Taylor series expansion with $\frac{v_{be}}{V_T} \ll 1$]

Thus, $$i_C = I_C + \frac{I_C}{V_T} v_{be}$$

$\Rightarrow$ small signal, $i_c = \frac{I_C}{V_T} v_{be}$

$\Rightarrow$ Transconductance, $g_m = \frac{I_C}{V_T}$.

* Can you prove that, $g_m = \left.\frac{\partial i_C}{\partial v_{BE}}\right|_{i_C = I_C}$?

Now, $i_C = I_S e^{v_{BE}/V_T}$

$$\Rightarrow \frac{\partial i_C}{\partial v_{BE}} = \frac{I_S}{V_T} e^{v_{BE}/V_T}$$

$$\Rightarrow \frac{\partial i_C}{\partial v_{BE}} = \frac{I_C}{V_T}.$$

* Can you also prove that, $g_m = \frac{I_C}{V_T}$ with base-width modulation?

* Unlike MOSFET where there is no gate current at DC, we have a base current in BJT at DC.

* Now,

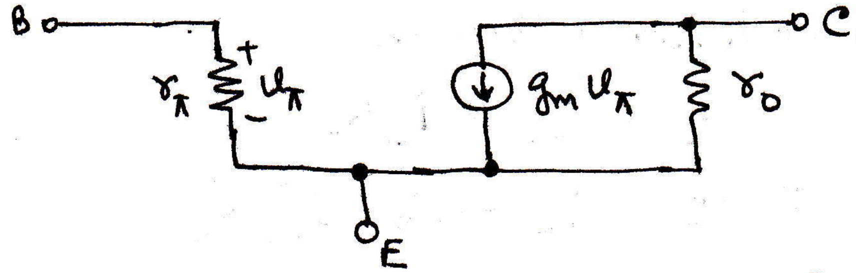
$$i_B = I_B + i_b$$

$$\Rightarrow i_B = \frac{I_C}{\beta} + \frac{I_C}{\beta V_T} v_{be}$$

Thus, $i_b = \frac{g_m}{\beta} v_{be}$

$\Rightarrow \frac{v_{be}}{i_b} = \frac{\beta}{g_m} = r_\pi$ = small signal input resistance between base and emitter.

Thus, small signal model of BJT is as follows:-



Emitter current & Input resistance at Emitter:-

$$i_E = \frac{i_C}{\alpha} = \frac{I_C}{\alpha} + \frac{i_c}{\alpha}$$

$$\Rightarrow i_E = I_E + i_e$$

where, $I_E = \frac{I_C}{\alpha}$ and $i_e = \frac{i_c}{\alpha}$.

Now, $i_e = \frac{i_c}{\alpha} = \frac{I_C}{\alpha V_T} v_{be}$

$$\Rightarrow i_e = \frac{I_E}{V_T} v_{be}$$

$$\Rightarrow r_e = \frac{v_{be}}{i_e} = \frac{V_T}{I_E}$$

We know, $g_m = \frac{I_C}{V_T}$. Thus,

$$r_e = \frac{\alpha}{g_m} \approx \frac{1}{g_m} \quad \ldots [\because \alpha \approx 1].$$

Relationship between r_π and r_e.

We know,

$$v_{be} = i_b r_\pi = i_e r_e.$$

$$\Rightarrow r_\pi = \frac{i_e}{i_b} r_e$$

$$\Rightarrow \boxed{r_\pi = (\beta+1) r_e}$$

VOLTAGE GAIN:-

Total collector voltage is,

$$v_C = V_{CC} - i_C R_C$$

$$\Rightarrow v_C = V_{CC} - (I_C + i_c) R_C$$

$$\Rightarrow v_C = (V_{CC} - I_C R_C) - i_c R_C.$$

$$\Rightarrow v_C = \underbrace{V_C}_{\text{DC bias Voltage}} - \underbrace{i_c R_C}_{\text{AC Variation.}}$$

Thus,

$$v_c = - i_c R_C$$

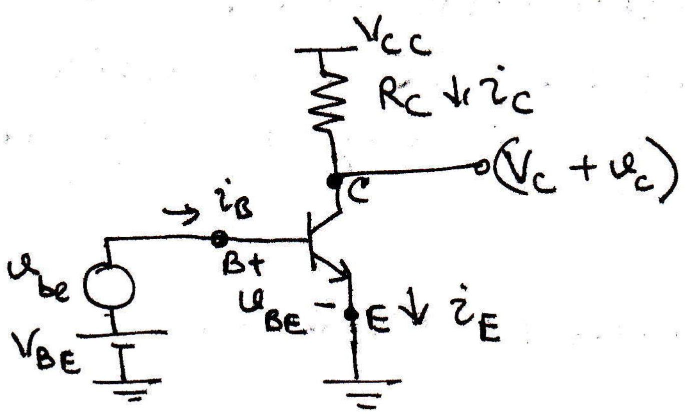
$$\Rightarrow v_c = - g_m v_{be} R_C,$$

$$\Rightarrow A_v = \frac{v_c}{v_{be}} = -g_m R_C.$$

We know, $g_m = \frac{I_C}{V_T}$ resulting in,

$$A_v = - \frac{I_C R_C}{V_T}.$$

SEPARATING THE DC AND AC QUANTITIES :-



$v_{BE} = V_{BE} + v_{be}$

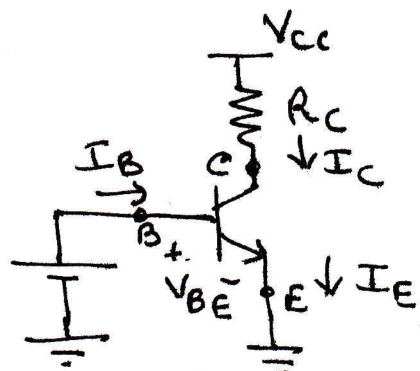
$v_C = V_C + v_c$

$i_B = I_B + i_b$

$i_C = I_C + i_c$

$i_E = I_E + i_e$.

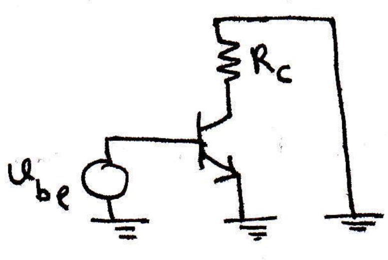
DC Equivalent Circuit :-



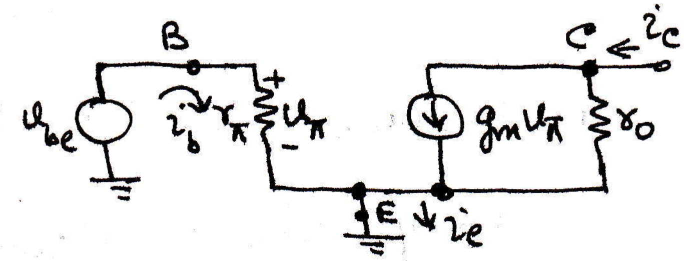
Obtain, V_{BE}, V_{CE}, I_C, I_E, and I_B.

AC Equivalent Circuit :-

Note that $v_{CC} = V_{CC} + v_{cc}$. But, $v_{cc} = 0 \Rightarrow v_{CC} = V_{CC}$. i.e. AC part of v_{CC} is $0 \Rightarrow$ a voltage source does not have a.c. variation.



$\Longrightarrow$



where, $r_\pi = \dfrac{\beta}{g_m}$

and, $g_m = \dfrac{I_C}{V_T}$.

Steps Of The Analysis

1. Determine the DC operating point of the BJT i.e. V_{BE}, V_C, and I_C. If the BJT is in active mode then I_B and I_E are given by $I_B = \frac{I_C}{\beta}$ and $I_E = \frac{I_C}{\alpha}$.

2. Calculate the small signall parameters :-

$$g_m = \frac{I_C}{V_T}$$

$$r_\pi = \beta / g_m$$

$$r_e = \frac{V_T}{I_E} = \frac{\alpha}{g_m}$$

$$r_o = \frac{V_A}{I_C} .$$

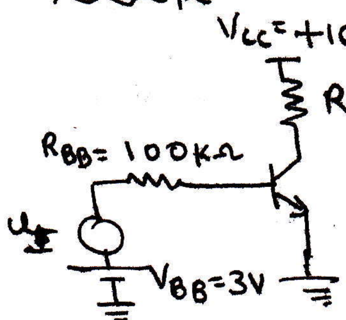
3. Remove all DC sources i.e.
   (a) remove all ~~DS~~ independent DC voltage sources i.e. replace them with short circuit.
   (b) remove all independent DC current sources i.e. replace them with open circuit.

   REMEMBER ONLY INDEPENDENT VOLTAGE & CURRENT SOURCES.

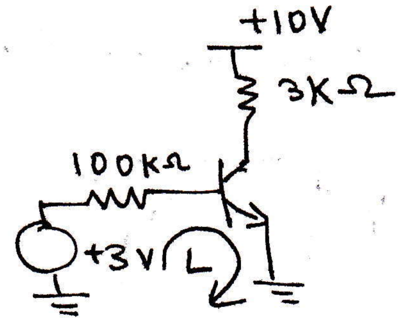
4. Replace the BJT with small signal model.

5. Analyze the resulting ~~given~~ small signal circuit.

Example:- $\beta = 100$, $V_A = \infty$



$\Longrightarrow$ D C Analysis



① D.C. Analysis:-

KVL in loop L gives,

$$3 = I_B 100K\Omega + V_{BE}$$

$$\Rightarrow 3 = I_B 100K\Omega + 0.7$$

$$\Rightarrow I_B = 23\mu A.$$

Thus, $I_C = 100 \times 23\mu A = 2.3mA$

$I_E = 2.323\ mA.$

$V_C = 10 - I_C R_C = 3.1V.$

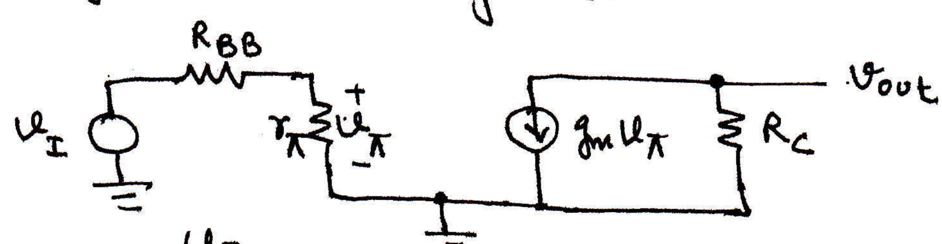
② Computing small signal parameters:-

$$g_m = \frac{I_C}{V_T} = \frac{2.3mA}{25mV} = 92m\mho$$

$$r_\pi = \frac{\beta}{g_m} = \frac{100}{92\times10^{-3}} = 1.09K\Omega$$

$$r_e = \frac{V_T}{I_E} = \frac{25mV}{2.323mA} = 10.8\Omega$$

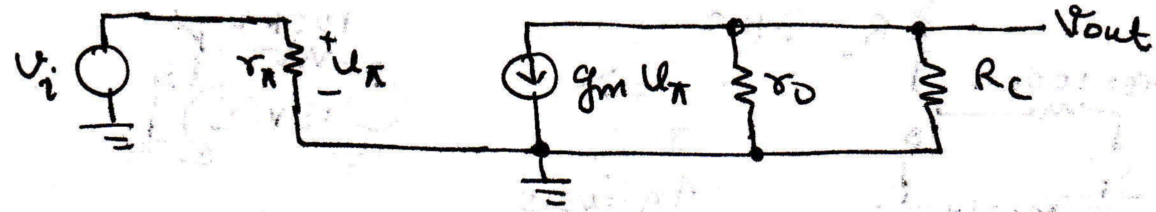
③ Small signal circuit diagram:-



Now, $v_\pi = \dfrac{v_I}{R_{BB} + r_\pi} r_\pi$. $\Rightarrow v_{out} = -g_m v_\pi R_C$

$$\Rightarrow A_v = \frac{v_{out}}{v_I} = -\frac{r_\pi}{R_{BB} + r_\pi} g_m R_C = -3.06$$

In the presence of Early Effect we should have,



Gain, $A_v = -g_m (r_o \parallel R_C)$.

* SOLVE EXAMPLE 5.15 → showing the waveforms at various points.